Substructure in the Globular Cluster System of the Milky Way: The Highest-Metallicity Clusters

Andreas Burkert

Max-Planck-Institut fur Astronomie, Königstuhl 17,

D-69117 Heidelberg,

Germany

Graeme H. Smith

University of California Observatories/Lick Observatory,

University of California,

Santa Cruz, California 95064

Received ______________________; accepted ______________________

To appear in Astrophysical Journal, Letters to the Editor

ABSTRACT

An analysis of the kinematical and spatial properties of the highest-metallicity globular clusters in the Galaxy, having metallicities of [Fe/H] > -0.8, indicates that these objects do not comprise a homogeneous population. Three subsystems are identified among these clusters.

i) The highest-mass clusters with $\log(M/M_{\odot}) > 5.5$ exhibit a very slow net rotation with a speed of $v_{\rm rot} = 24 \pm 23$ km/s and $v_{\rm rot}/\sigma_{\rm los} = 0.3$, indicative of a a centrally condensed, relatively-high-metallicity subsystem.

ii) Roughly half of the lower-mass clusters appear to be located in an elongated bar-like structure which passes through the Galactic Center, and has similar properties to the central stellar bar of the Milky Way.

iii) The remaining lower-mass clusters exhibit very rapid net rotation, with a rotation speed of $v_{\rm rot} = 164 \pm 6$ km/s and $v_{\rm rot}/\sigma_{\rm los} = 6$. These clusters are located in the Galactic plane, within a ring of 4 to 6 kpc radial distance from the Galactic Center.

The highest-mass clusters may have formed during relatively advanced stages of the dissipative evolution of the inner Galactic halo. Although the lower-mass bar clusters have kinematical properties which are similar to the highest-mass clusters, their spatial distribution suggests that they may be associated with the formation of the Galactic stellar bar or bulge. The lower-mass ring clusters appear to be real disk objects. They may represent a stage in cluster formation that was intermediate between that of the halo globular clusters and the oldest extant open clusters.

Subject headings: Galaxy: formation – Galaxy: halo – globular clusters: general

1. Introduction

Since the pioneering work of Shapley (1918) the properties of the Galactic globular cluster system have been seen as valuable tracers of the structure and history of the Galactic halo (van den Bergh 1995). Zinn (1985), Armandroff & Zinn (1988), and Armandroff (1989), on the basis of correlations between metallicity and kinematics, divided the globular cluster population of the Galaxy into a halo and a disk system, the clusters of which have metallicities of [Fe/H] < -0.8 and [Fe/H] > -0.8, respectively. This has lead to a model in which the metal-richest globular clusters belong to a kinematically uniform disk system. This letter presents a new analysis of the kinematical and spatial properties of the highest-metallicity ([Fe/H] > -0.8) Galactic globular clusters which shows that they may not constitute a homogeneous population. Instead, if these clusters are grouped on the basis of their mass, several subsystems can be identified. We have taken advantage of the April 1996 version of the *Catalog of Parameters for Milky Way Globular Clusters* compiled by Harris (1996). This was obtained through the World Wide Web from the site (URL) http://www.physics.mcmaster.ca/Globular.html. Our kinematical analysis follows the lines of Frenk & White (1980, 1982), Zinn (1985), and Armandroff (1989), but our approach differs from theirs in that we divide the metal-richest clusters into two subgroups according to cluster mass.

2. Mathematical Framework

Throughout this paper a standard X, Y, Z Galactocentric coordinate system is adopted (cf. Mihalas & Binney 1981). The Solar motion is taken to be in the direction $l_s = 57°$, $b_s = 23°$, with a velocity $S = 20$ km/s (Zinn 1985). The three components of the Solar velocity relative to the Local Standard of Rest (LSR) are then $(U_\odot, V_\odot, W_\odot) = (10.1, 15.5, 7.5)$ km/s. The velocity of a globular cluster with respect to the LSR ($V_{\rm LSR}$) is computed from

the above components of the Solar motion and the heliocentric radial velocity of the cluster (Mihalas & Binney 1981). The radial velocity $V_{\rm S}$ of a cluster with respect to a *stationary* observer at the location of the Sun is $V_{\rm S} = V_{\rm LSR} + 220$ (km/s) $\cos A$, where A is the angle between the apex of the LSR and the cluster's position on the sky, $\cos A = \sin l \cos b$ and the rotational velocity of the LSR is assumed to be 220 km/s.

Analysis of the bulk rotation of a system of globular clusters depends on that system's rotation curve. In the case of a constant systematic rotation speed $v_{\rm rot}$ without a global radial motion (Frenk & White 1980)

$$V_{\rm S} = v_{\rm rot} \cos \Psi + v_{\rm pec} \tag{1}$$

where

$$\cos \Psi = \frac{R_\odot \cos A}{\sqrt{R^2 \cos^2 A + (R_\odot - R \cos b \cos l)^2}}, \tag{2}$$

$v_{\rm pec}$ is the line-of-sight peculiar velocity of a cluster, and R is the cluster's Galactocentric distance. The Galactocentric distance of the Sun is taken to be $R_\odot = 8$ kpc. In the case of rigid-body rotation with a uniform angular velocity of ω (Kinman 1959, Zinn 1985)

$$V_{\rm S} = \omega R_\odot \cos A + v_{\rm pec}. \tag{3}$$

An unbiased estimate of $v_{\rm rot}$ can be obtained by the following sum over all clusters (Frenk & White 1980):

$$v_{\rm rot} = \frac{\sum_i \cos \Psi_i \; V_{\rm S,i}}{\sum_i \cos^2 \Psi_i} \pm \frac{\sigma_{\rm los}}{\sqrt{\sum_i \cos^2 \Psi_i}} \tag{4}$$

with a similar equation for $\omega R_\odot$ and $\cos A$. The line-of-sight velocity dispersion $\sigma_{\rm los}$ of the sample is determined by inserting $v_{\rm rot}$ or $\omega R_\odot$ into equations 1 and 3, respectively, and calculating the dispersion in $v_{\rm pec}$.

Globular cluster masses M were calculated from the integrated absolute visual magnitudes ($M_{\rm V}$) tabulated by Harris (1996). A mass-to-light ratio of $(M/L)_{\rm V} = 3$ was assumed (Chernoff & Djorgovski 1989).

3. The Two Subsystems Among the Highest-Metallicity Globular Clusters

In this section we divide the metal-richest Galactic globular clusters, which we take to be those with [Fe/H] > -0.8, into two mass groups: a *high-mass* group for which $\log M/M_\odot > 5.55$ ($M_{\rm V} < -7.9$), and a *lower-mass* group, containing clusters of mass smaller than this. The kinematical properties of these two groups are summarised in columns 2 and 3 of Table 1. The parameters listed include the number of clusters in each group N, the rotation speed $v_{\rm rot}$ for the case of a flat rotation curve and the value of ω for the case of rigid-body rotation, as well as the standard deviations in these values. Also given are the line-of-sight velocity dispersions $\sigma_{\rm los}$, the mean height above the Galactic plane $Z_{\rm mean}$, and the mean radial distance in the Galactic plane $R_{\rm mean}$ for each group. With the caveat that the number of clusters is relatively modest, the entries in Table 1 indicate that the kinematical properties of the high-mass and lower-mass clusters are different. While the high-mass clusters show little or no rotation, the low-mass clusters exhibit rotation with a significance level of $v_{\rm rot} \approx 8\sigma$. These results suggest that the high-mass clusters define a spheroidal inner-halo-like subsystem whereas the low-mass clusters represent a disk-like component.

3.1. The Lower-Mass Clusters: $\log M/M_\odot < 5.55$

Kinematical and spatial data for the lower-mass clusters are plotted in the upper and lower panels, respectively, of Figure 1. Least-squares fits to the velocity data for the entire set of lower-mass clusters are shown as short-dashed lines in the upper panels. Two groups of clusters can be distinguished in the top panels of Figure 1. One group (open circles) exhibits a relatively well-defined relationship between $V_{\rm S}$ and both $\cos A$ and $\cos\Psi$. The remaining clusters are all within a small $\cos A$ range ($-0.2 < \cos A < 0.2$) and are represented by filled circles. These two groups are also relatively distinct in the lower panels of Figure 1. With the exception of Ter 7 which is located at Galactocentric coordinates $(X, Y, Z) = (-12.5, 1.2, -7.5)$ kpc and probably belongs to the Sagittarius dwarf spheroidal galaxy (Da Costa & Armandroff 1995), the group with small $\cos A$ falls within a centrally concentrated, bar-like configuration that is extended in the X direction and has $Y \approx 0$; the clusters in this group will be referred to as "bar clusters." The remaining clusters (open circles) fall within a ring around the Galactic Center having an inner and an outer radius of ≈ 4 and 6 kpc respectively; these objects will be referred to as the "5-kpc-ring" clusters.

A bar-like feature in the space distribution of globular clusters was noted by Woltjer (1975) and Harris (1976), who suggested that it could be an artifact of distance measurement errors for clusters in directions close to that of the Galactic Center. Frenk & White (1980) performed Monte Carlo simulations to assess this possibility. They found that errors in distance moduli would have to be as large as 1.0 mag to explain the bar. Whereas the accuracy of distance modulus measurements have increased since the time of Woltjer's (1975) analysis, the bar is more prominent in Figure 1 than in the data of Woltjer, the opposite to what would be expected if the bar were an observational artifact. Note that there is also strong evidence for a bar-like distribution of stars and molecular gas in the Galactic bulge (see the review by Freeman 1996). It is striking that the stellar bar has a

very similar orientation, spatial distribution, and rotational velocity to the subsystem of "bar clusters", indicating a common origin.

Separate least-squares fits were made to the velocity data for the subset of "bar" clusters and for the subset of "5-kpc-ring" clusters. The results are given in columns 4 and 5 of Table 1, and the fits for the "5-kpc-ring" subsystem are shown as long-dashed lines in Figure 1. Two points deserve emphasis.

(i) The small range of $\cos A$ for the *bar clusters* leads to large errors in ω if one assumes solid-body rotation. Nevertheless, the value of $\omega = 59$ km/s/kpc for these clusters is in excellent agreement with Zhao's (1994) estimated angular velocity of the central stellar bar of $\omega = 60$ km/s/kpc. The assumption of rigid body rotation might therefore be the physically appropriate model for the "bar clusters." It is interesting that all the clusters of the bar system have positive V_S values. This bulk flow may indicate that the bar is a transient phenomenon.

(ii) The *5-kpc-ring* clusters constitute a rapidly rotating subsystem, with only a small velocity dispersion. These clusters seem to be members of the Galactic disk. The rotation speed at $R = 5$ kpc, derived from the solid-body assumption (upper-right panel of Figure 1) is 120 km/s, which compares with 164 km/s under the assumption of a flat rotation curve. In addition, $v_{\rm rot}/\sigma_{\rm los} = 6$, indicative of a disk with well-organised rotation. This subgroup of "5-kpc-ring" clusters has kinematics not greatly different from the old open cluster system of the Galactic disk, which has a scale height of 375 pc (Janes & Phelps 1994) and kinematics of $v_{\rm rot} = 211 \pm 7$ km/s and $\sigma_{\rm los} = 28$ km/s (Scott, Friel, & Janes 1995). The difference in the rotation speeds of these two cluster systems may be partly related to the differences in their average age and Galactocentric distance.

The lower-mass "5-kpc-ring" globular clusters might represent "missing links" between the globular clusters of the halo and the open clusters of the Galactic disk. As illustrated

in Figure 3 of Hufnagel & Smith (1994), for example, no old open clusters are known with Galactocentric distances of less than 7 kpc. It may be that old open clusters did not form within 7 kpc of the Galactic Center; and that more populous globular-like clusters, like M71, were instead formed in this region of the Galaxy. Alternatively, open clusters that formed at $R < 7$ kpc may have been disrupted by interactions with molecular clouds. The objects more likely to survive this process would have been the higher-mass globular clusters.

3.2. The High-Mass Clusters: $\log M/M_{\odot} > 5.55$

The positional and kinematical data for those globular clusters having $\log M/M_{\odot} > 5.55$ and [Fe/H] > -0.8 are shown in Figure 2. The fact that $v_{\rm rot}/\sigma \leq 1$ indicates that the high-mass, metal-richest globulars are not members of a true rotating disk system. The formal solution of $v_{\rm rot} = 24.3$ km/s is heavily weighted by the cluster NGC 104 (47 Tuc) with $\cos\Psi = -0.68$ and $V_{\rm S} = -145$ km/s; excluding this object would lead to counter-rotation with $v_{\rm rot} = -10$ km/s for the remaining sample of clusters, further strengthening the conclusion that these clusters are not part of a rotating disk population.

Rather than being members of the disk, these clusters may instead belong to a metal-enriched inner-halo component. The velocity dispersion among these clusters is not as large as for the system of more metal-poor Galactic halo globular clusters. This result is in agreement with Frenk & White (1980) who found that the observed line-of-sight velocity dispersion of the halo cluster population increases significantly with Galactocentric distance, indicating a non-isothermal cluster distribution function. The high-mass relatively-high-metallicity clusters might therefore be part of a more centrally condensed and kinematically cooler inner component of the Galactic halo. Formed at times when the interstellar medium in the proto-galaxy had experienced dissipational contraction and the metallicity had increased to relatively high values, these clusters may represent the

last remnants from the true epoch of globular cluster formation in the Galactic halo.

3.3. Statistical Analysis

A statistical investigation of the difference between the low-mass and high-mass clusters depicted in Figures 1 and 2, respectively, is affected by the low number (7) of high-mass clusters. To take account of this limitation, Monte Carlo simulations were performed in which random samples of seven clusters were generated from a population with given average rotational velocity V_{pop} and velocity dispersion σ_{pop} similar to that of the low-mass clusters. For each sample generated, the average rotational velocity $v_{\rm rot}$ was calculated using equation 4. The results for a large number of artificial samples were combined to give the probability that the rotation speed for such a sample is $v_{\rm rot} < 24.3$ km/s, corresponding to rotation that is as slow as observed for the high-mass system of clusters. The data for each set of seven clusters were generated as follows: first, a value for $\cos\Psi$ was chosen, randomly distributed between -1 and $+1$. The cluster velocities $V_{\rm S}$ were then generated assuming a normal probability distribution function:

$$P(V_{\rm S}) = exp\left(-\frac{[V_{\rm S} - V_{pop}\cos\Psi]^2}{2\ \sigma_{pop}^2}\right) \tag{5}$$

with values of V_{pop} and σ_{pop} chosen to be representative of the low-mass system of clusters.

Using this method, we find that there exists a 10% probability that the high-mass clusters are drawn from the same kinematical population as the combined sample of low-mass clusters. Comparing the high-mass clusters and the low-mass bar clusters, we find a 51% probability that these two samples have similar kinematical properties. On the other hand, the velocity distributions of high-mass clusters and low-mass ring clusters are significantly different, with a probability of less than 4×10^{-6} that both samples result from

the same population.

In summary, we can rule out with a high probability that the high-mass clusters have an average rotational velocity and a velocity dispersion similar to the ring clusters. They appear to be two distinct subsystems. The relation of the bar clusters to the high-mass clusters is not clear from the present analysis. The similar kinematical properties of both subsystems (assuming a constant rotational velocity) suggests that they may be drawn from the same or related populations. However, the more extended spatial distribution of the high-mass clusters indicates that this subsystem is part of the inner halo. The origin of the bar clusters, on the other hand, is more likely related to the formation of the central stellar bar or bulge. The formation of the inner halo and Galactic bulge/bar could also be coupled.

4. Summary

We propose that the following three subsystems can be distinguished among the highest-metallicity ([Fe/H] > -0.8) globular clusters of the Galaxy: *i) a centrally condensed halo subsystem of high-mass clusters, ii) a bar subsystem of lower-mass clusters, and iii) a rapidly-rotating disk subsystem of lower-mass clusters, many of which fall within a ring about the Galactic Center of radius 4-6 kpc.* These subsystems indicate that the population of relatively-high-metallicity globular clusters is more heterogeneous than has hitherto been expected from the concept of a single disk population.

If the high-mass, higher-metallicity globular clusters really are members of the Galactic halo as suggested above, then it follows that high-mass ($M > 3 \times 10^5\ M_{\odot}$) cluster formation only took place in the Galactic halo, not in the disk. This suggests that the maximum mass of star clusters which formed in the Galaxy may have decreased with time, perhaps along the lines of the following scenario. The halo supported massive cluster formation, possibly

under starburst-like conditions in massive clouds (Murray & Lin 1989; Harris & Pudritz 1994; Brown et al. 1995; Burkert et al. 1996). However, as the interstellar medium collapsed into the center and the equatorial plane and the metallicity built up, cluster formation tended to produce the low or intermediate-mass globular clusters ($\log M/M_{\odot} < 5.5$) found in the bar or the 4-6 kpc ring noted in Figure 1. As the disk built up further from the inside out, the sites of cluster formation propagated outwards through the disk into regions beyond 7 kpc from the Galactic Center. The typical masses of clusters being formed at this time were markedly lower, with open clusters like NGC 6791 and NGC 188 being produced.

A. Burkert thanks the staff of UCO/Lick Observatory for their hospitality during two visits on which this work was done.

REFERENCES

Armandroff, T. E., & Zinn, R. 1988, AJ, 96, 92

Armandroff, T. E. 1989, AJ, 97, 375

Brown, J. H., Burkert, A., & Truran, J. W. 1995, ApJ, 440, 666

Burkert, A., Brown, J. H., & Truran, J. W. 1996, in The History of the Milky Way and its Satellite System, eds. A. Burkert, D. Hartmann, & S. R. Majewski, in press

Chernoff, D. F., & Djorgovski, S. 1989, ApJ, 339, 904

Da Costa, G. S., & Armandroff, T. E. 1995, AJ, 109, 2533

Freeman, K. C. 1996, in IAU Colloq. 157, Barred Galaxies, ASPCS 91, eds. R. Buta, D. A. Crocker, & B. G. Elmegreen (San Francisco: Astr. Soc. Pac.), 1

Frenk, C. S., & White, S. D. M. 1980, MNRAS, 193, 295

Frenk, C. S., & White, S. D. M. 1982, MNRAS, 198, 173

Harris, W. E. 1976, AJ, 81, 1095

Harris, W. H., & Pudritz, R. E. 1994, ApJ, 429, 177

Harris, W. E. 1996, The Catalog Of Parameters for Milky Way Globular Clusters

Hufnagel, B., & Smith, G. H. 1994, PASP, 106, 1068

Janes, K. A., & Phelps, R. J. 1994, AJ, 108, 1773

Kinman, T. D. 1959, MNRAS, 119, 157

Mihalas, D., & Binney, J. 1981, Galactic Astronomy (San Francisco: Freeman & Co).

Murray, S. D., & Lin, D. N. C. 1989, ApJ, 339, 933

Scott, J. E., Friel, E. D., & Janes, K. A. 1995, AJ, 109, 1706

Shapley, H. 1918, ApJ, 48, 154

van den Bergh, S. 1995, AJ, 110, 1171

Woltjer, L. 1975, A&A, 42, 109

Zhao, H. 1994, PhD thesis, Columbia University

Zinn, R. 1985, ApJ, 293, 424

This manuscript was prepared with the AAS LaTeX macros v4.0.

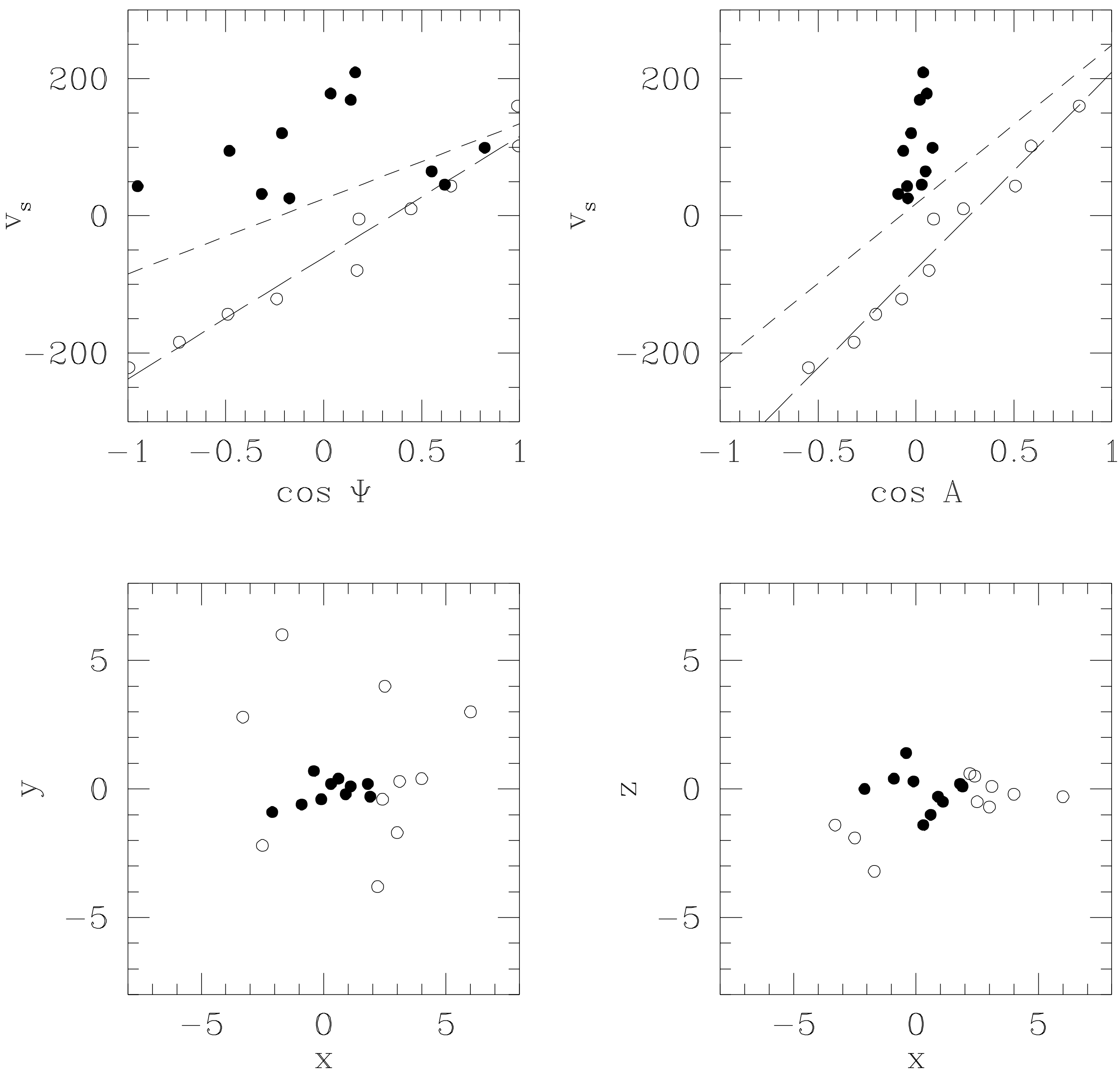
Figure Captions

Fig. 1.— The kinematical and spatial properties (upper and lower panels respectively) of Galactic globular clusters with metallicities of [Fe/H] > -0.8 and masses $\log(M/M_{\odot}) < 5.55$. The filled circles represent clusters of the "bar system", while open circles denote the "5-kpc-ring" clusters. The short-dashed lines show the least-squares fits to the velocity data for the entire sample. The long-dashed lines show fits to the data for the "5-kpc-ring" clusters only.

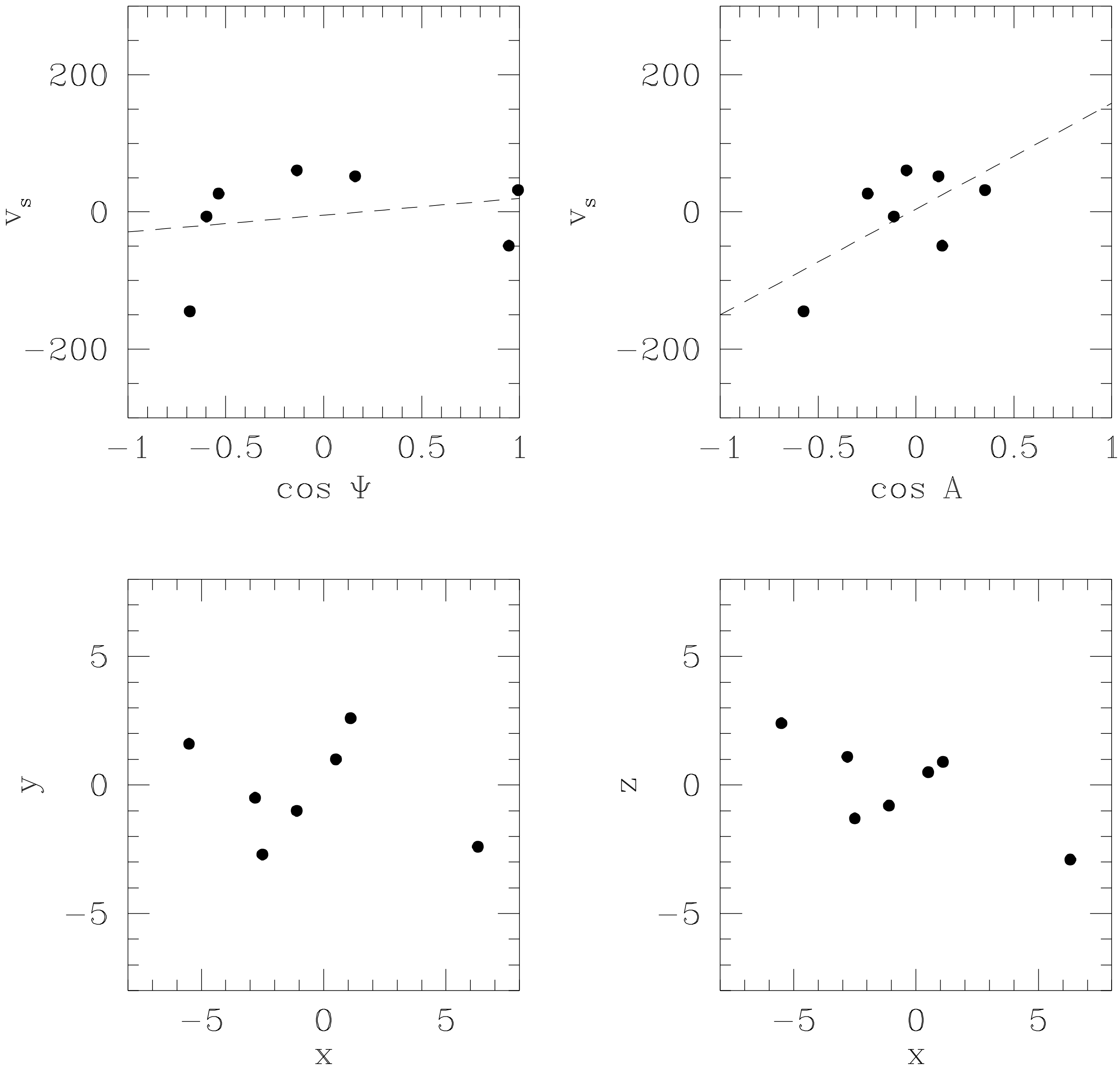
Fig. 2.— The kinematical and spatial properties of Galactic globular clusters with metallicities of [Fe/H] > -0.8 and masses $\log(M/M_{\odot}) > 5.55$.

Table 1. Kinematical and Spatial Properties of Globular Clusters with [Fe/H] > -0.8

	higher-mass	lower-mass	bar	5-kpc-ring
N	7	21	11	10
$v_{\rm rot}$ [km/s]	24.3 ± 23.2	113.2 ± 14.0	30.2 ± 23.0	163.7 ± 5.8
ω [km/s/kpc]	15.2 ± 9.9	24.3 ± 5.3	58.6 ± 173.5	23.7 ± 1.3
$\sigma_{\rm los}$ [km/s] (flat)	70.4	101.2	62.7	26.0
$\sigma_{\rm los}$ [km/s] (rigid)	55.7	98.6	55.3	22.8
$Z_{\rm mean}$ [kpc]	0.45	0.22	0.33	0.31
$R_{\rm mean}$ [kpc]	3.49	3.18	2.18	4.27



v_s
cos Ψ
cos A
y
z
x



200
0
−200
v_s
−1
−0.5
0
0.5
1
cos Ψ
200
0
−200
v_s
−1
−0.5
0
0.5
1
cos A
5
0
−5
y
−5
0
5
x
5
0
−5
z
−5
0
5
x